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Effect of Pre-stress in Steel Strips to Strengthen Unreinforced Brick Masonry Walls under Axial Loads

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Abstract. Using steel strips to strengthen the existing unreinforced masonry walls has competitive advantages, which includes no wet work, avoidance of formwork, time saving, ease of installation, minimal increase of dimensions, no requirement for material strength of the existing walls and good reversibility. In this paper, seven specimens were fabricated and tested under axial loads for obtaining the effect of pre-stress in steel strips to strengthen unreinforced brick masonry walls. Test results showed pre-compression stress in the vertical steel strips could increase the load of cracks in the single brick in the wall, otherwise steel strips only improved the load of continuous cracks and the failure load, and the axial stiffness of the wall; when the transverse steel strips were pre-tensioned, it could further improve the failure load and the later axial stiffness of the strengthened wall.

1. Introduction

A significant part of the building stock is masonry structures and they are still in service over the world, furthermore a few of which are also historical buildings with high historical, artistic and scientific value. Some of these existing masonry buildings have been in use for many years and need strengthening for either improving their static-carrying capacity or seismic performance primarily due to deterioration of mechanical properties of materials (block and bonding material), reduction in the cross-sectional area of bearing walls because of renovation of the building, or/and improvement in seismic requirements. In the recent 20 years, strengthening techniques of unreinforced masonry structures has received more and more attention of civil engineers and researchers [1-7].

Eslamlou et al. [8] have reviewed the effect of different strengthening techniques to improve the seismic performance of unreinforced masonry structures, and considered using steel strips as an efficient retrofitting technique because of its enhancement of lateral load resistance, displacement capacity and ductility of structure. Although the behavior of existing unreinforced brick masonry strengthened by steel strips has been tackled by several researches [9-11], test data involving more influence parameters, such as applying pre-stress in steel strips, are very limited in the literature. Applying pre-stress in steel strips to strengthen the existing masonry walls can reduce stress lag between them. In response to this lack, the primary objective of the research described in this paper was to investigate the axial behavior of brick masonry strengthened with bolted steel strips, considering the effect of pre-stress in steel strips. In addition, hereafter the masonry wall in this paper is only referred to the brick masonry wall.

2. Experimental program

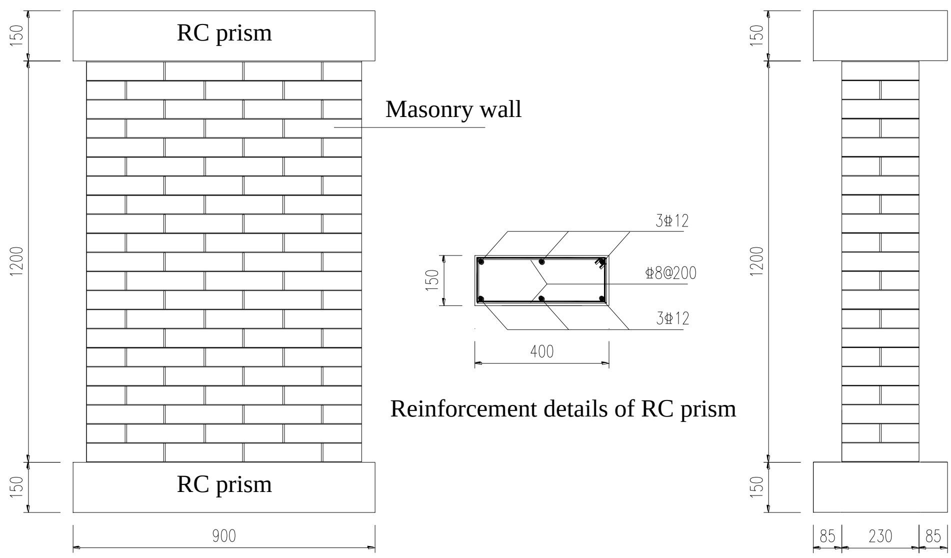
2.1 Test specimens

In this experimental investigation seven masonry wall panels were designed and tested under axial loads. The wall panels were made of fired common bricks with dimensions of 230 mm × 100 mm × 45 mm and about 10 mm thick bed joints made of cement-lime mortar. The geometry of all wall panels was designed to be 820 mm in width, 230 mm in thickness and 1200 mm in height, and the final real size for them was about 825 mm × 230 mm × 1205 mm. In addition, each masonry panel was constructed on a reinforced concrete (RC) prism (900 mm long, 400 mm wide, 150 mm high), whereas a RC prism of the same dimensions was provided at top of each specimen, to ensure uniform distribution of the applied compressive load on the masonry.

Each specimen was given a name, and UW refers to the unreinforced masonry wall as a reference specimen; SW refers to the masonry wall strengthened with steel strips, followed by a number which defines whether pre-compression stress or pre-tension stress was applied to the steel strips and different preload levels of the masonry wall. The details of all specimens are summarized in Table 1 and shown in figure 1. It should be noted that, in Table 1, 2V refers to two vertical steel strips; and 2T stands for two transverse steel strips. In addition, the pre-compression stress was designed to be 50 MPa, and the pre-tension stress was 20 MPa.

Table 1. Details of specimens

Specimen	Strength of mortar	Strength of brick	Configuration of steel strips	preload / peak load	Pre-compression in vertical strips (Y/N)	Pre-tension in transverse strips (Y/N)
UW	5.0 MPa (M5)	25 MPa (MU25)	/	0	/	/
SW1			2V+2T	0	N	N
SW2				0	Y	N
SW3				0	N	Y
SW4				21%	Y	N
SW5				41%	Y	N
SW6				21%	Y	Y



(1) Specimen UW

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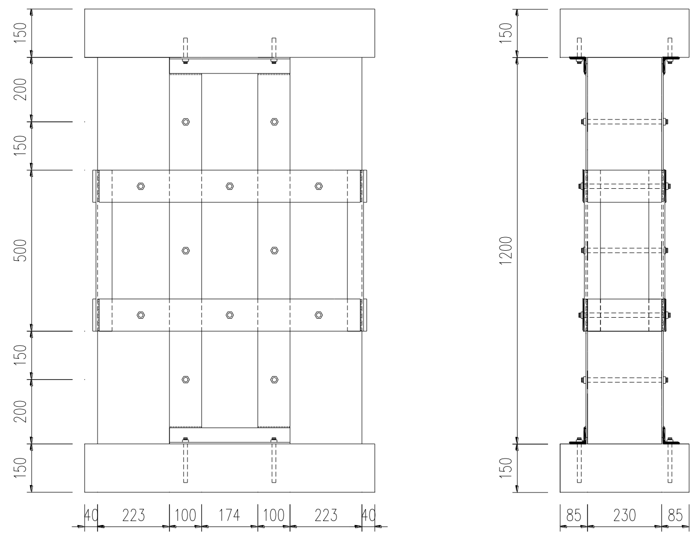
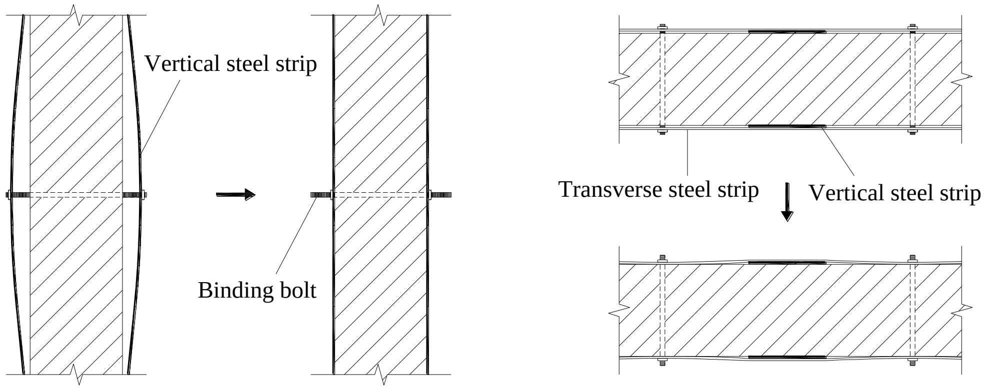


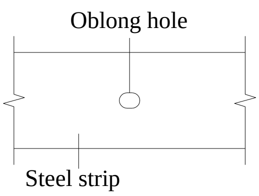
(2) Specimens SW1~SW6

Figure 1. Details of specimens

For the strengthened specimens, in addition to the steel strips, some other parts including steel angles, battened plates and bolts were also required (figure 1), which was used to transmit force more evenly at the ends. The thickness of all the vertical steel strips was 5 mm, and that was 3 mm for all the transverse steel strips. All the binding bolts were 14 mm diameter threaded steel rods, but the anchoring bolts were 12 mm. Here the anchoring bolt was fixed through professional structural adhesive with a depth of 120 mm. For the specimens with pre-stresses steel strips, i.e. specimens SW2~SW6, whether the pre-stressing in the vertical or transverse steel strips was achieved by tightening the bolts, the detailed fastening process is shown in figure 2. Note that the shape of the holes in the steel strips required to be pre-stressed should be oblong (figure 2c), which allows the steel strip to move relatively freely when deformed. Some partially prepared test specimens are shown in figure 3; however for some other strengthened specimens with preloads, the vertical steel strips could only be installed completely when they were loaded (under a predetermined load).



(a) Pre-stressing in vertical steel strips (b) Pre-stressing in transverse steel strips



(c) Details of hole

Figure 2. Schematic diagram of pre-stressing in steel strips

Figure 3. Partially fabricated test specimens

2.2 Material properties

In this study, the mechanical properties of the main materials which determine the compressive behavior of test specimens, including steel plates, binding bolt, brick and mortar, were determined following the relevant Chinese standards [12-14]. The thicknesses of the steel plates were 3 and 5 mm. The mechanical properties of the steel plate, binding bolt, brick and mortar were determined using three samples for each type of steel plate, three samples for the bolt and mortar, and ten samples for the brick. The average values of the test data are reported in Table 2.

Table 2. Materia properties

Element	Thickness/diameter (mm)	Yield strength (MPa)	Ultimate strength (MPa)	Elastic modulus (MPa)
Steel plates	3	370.0	515.6	206000
	5	381.6	519.6	206000
Binding bolts	14	576.4	694.5	210000

Element	Compressive strength (MPa)
Mortar	5.14
Brick	27.6

2.3 Test setup and instrumentation

The specimens were tested under axial loads applied by 2500 kN Four-column Hydraulic Press (figure 4). The specimens were instrumented to measure the axial displacement with 8 linear variable differential transformers (LVDTs) at the top and bottom corners.

Figure 4. Test setup

All specimens were preloaded to 60 kN to ensure that the instrumentation was working properly and there was no slack in the system. The preload was then released and the readings were set to zero. The loading test was carried out in force control by increments of 60 kN with a velocity of 30 kN/min. The specimen after each loading increment was left to rest for 10 minutes before readings were recorded.

3. Test results and discussion

3.1 Failure mode

For the specimen UM, i.e. the unreinforced masonry wall, as the applied load increased, the vertical cracks only appeared in the single bricks of the wall, and then the single brick cracks joined into a few continuous cracks. As more and more continuous cracks appeared and the length of the cracks was more than half the height of the wall (figure 5), the wall approached its failure load. Note that there was no crushing in the wall when the peak load (i.e. the applied load could not be increased) was reached.

(a) Front view (b) Side view

Figure 5. Failure mode of specimen UM

For the masonry walls strengthened with steel strips, their failure process was not exactly the same because of the different initial stress state of steel strips and the different preload level of the masonry wall.

For specimen SW1, all the steel strips used for strengthening the walls were not pre-stressed. During the loading process, the vertical steel strips showed visible local buckling deformation (figure 6a) when cracks appeared in some single bricks. As the load increased, the cracks in the single bricks gradually developed into several continuous cracks (figure 6b), and the cracks' width would become bigger and bigger until the peak load was reached. In the final stage of failure, the length of these cracks was shorter than those in specimen UW, and the edges of the top and bottom of the wall were crushed because they were the weaker part, i.e. without confinement from steel strips. Therefore, the masonry wall strengthened with steel strips had a better deformation capacity than the unreinforced masonry wall.

(a) local buckling of steel strips (b) Cracks in the masonry wall

Figure 6. Failure mode of specimen SW1

For specimens SW2 strengthened with vertical and transverse steel strips, and vertical steel strips were applied pre-compression stress. For specimens SW4 and SW5 strengthened with vertical and transverse steel strips, not only the vertical steel strips were applied pre-compression stress, but also the walls were preloaded. All of these specimens had a similar failure process as specimen SW1. The final failure mode of specimen SW2 is shown in figure 7.

(a) local buckling of steel strips (b) crushing of masonry

Figure 7. Failure mode of specimen SW2

For specimens SW3 and SW6 strengthened with the vertical steel strips and transverse steel strips, the local buckling deformation in the vertical steel strips appeared after the occurrence of continuous cracks in the masonry wall, and other failure characteristics were similar to specimen SW1. It can be seen that the transverse steel strips with pre-tension stress could provide better lateral support for the vertical steel strips and delay the occurrence of visible local buckling deformation in the vertical steel strips.

3.2 Cracking load and peak load

Table 3 presented the cracking load and peak load of all the specimens. Note that the cracking load of the brick masonry wall includes two cases: (1) the crack only appears in the single brick, which is represented by N_s; (2) the crack passes through a few bricks, i.e. the cracks that appear in the single bricks are connected, which is represented by N_c. In addition, the peak load (N_p) is also known as the failure load, which means that the load cannot continue to increase. In order to better understand the strengthening effect of steel strips, Table 3 also listed the increase of the strengthened specimens (SW1~SW6) compared with the unreinforced specimen (UW) in terms of two types of cracking load and peak load.

From Table 3, it can be obtained that using steel strips, regardless of whether pre-stressing in steel strips or preload on the masonry wall was applied, can improve the load of the occurrence of continuous cracks by 31%~56% and peak load by 33%~43%, respectively. However, in terms of the degree of improvement, several meaningful conclusions can be summarized in the following: (1) Applying pre-compression stress in the vertical steel strips is effective in terms of improving the load of cracking only in the single bricks, which shows that applying pre-compression stress in the vertical steel strips can make it work in advance to bear the applied load on the specimen. As it is well known when the masonry wall was strengthened with steel strips by dry connection, it is difficult for vertical steel strips to cooperate with the masonry wall ideally in the initial stage of loading due to the installation defects (e.g. gaps between the ends of the vertical steel strips and the masonry wall). (2) Applying pre-tension stress in the transverse steel strips can only further improve the peak load, which shows that the pre-tension stress in the transverse steel strips can provide a better support for the vertical steel strips. (3) Preload on the brick masonry wall, when it would not produce cracks, will not influence obviously the strengthening effect with steel strips.

Table 3. A summary of test results

Specimen	N_s / kN	Increase of N_s (%)	N_c / kN	Increase of N_c (%)	N_p / kN	Increase of N_p (%)
UW	600	—	960	—	1260	—
SW1	540	*-10*	1500	56	1740	38
SW2	720	20	1440	50	1680	33
SW3	540	*-10*	1320	38	1800	43
SW4	960	60	1260	31	1680	33
SW5	900	50	1440	50	1680	33
SW6	960	60	1320	38	1800	43

3.3 Load-displacement curves

Based on the average displacement of four points, the load-displacement curves of all the specimens were plotted, which can represent the overall performance of the specimens.

Figure 8 shows the load-displacement curves of specimens UW, SW1 and SW2. In specimen SW2, a force of 10 kN was preloaded for installing vertical steel strips with pre-compression stress, and a reverse displacement was still taken place in figure 8. By comparing the curves of specimens SW1 and SW2, it shows that applying pre-compression stress in vertical steel strips not only improve the later axial stiffness of the strengthened specimen, but also effectively increase the initial axial stiffness. In addition, applying pre-compression in vertical steel strips has no effect on increasing its peak load.

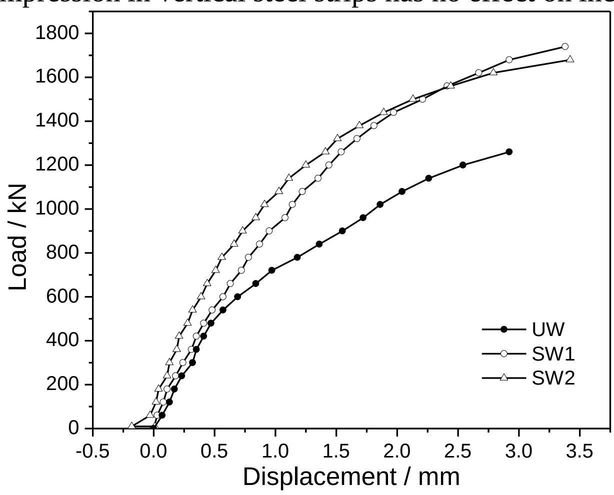


Figure 8. Load-displacement curves of specimens UM, SW1 and SW2

Figures 9 and 10 show the load-displacement curves of specimens SW1, SW3, SW4 and SW6. It can be seen that whether the vertical steel strip has pre-compression stress or the masonry wall has preload, applying pre-tension stress in the transverse steel strips can slightly increase the peak load and the later axial stiffness of the strengthened specimen. When pre-tension stress applied in the transverse steel strips, it could help transverse steel strips to work in advance and provide a better support to the vertical steel strips.

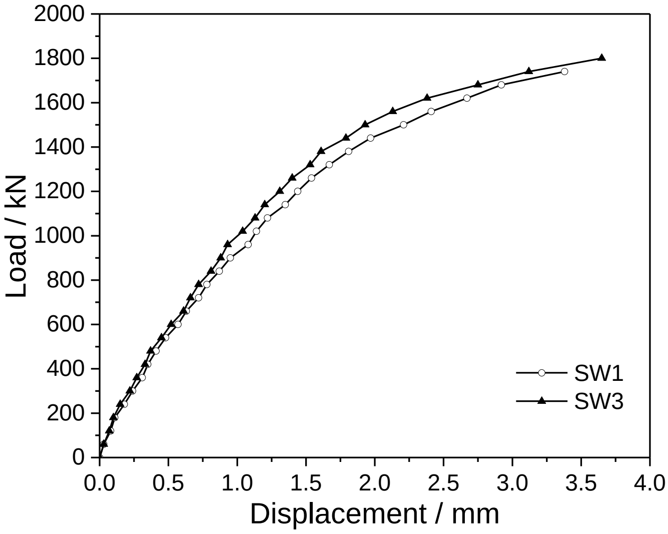


Figure 9. Load-displacement curves of specimens SW1 and SW3

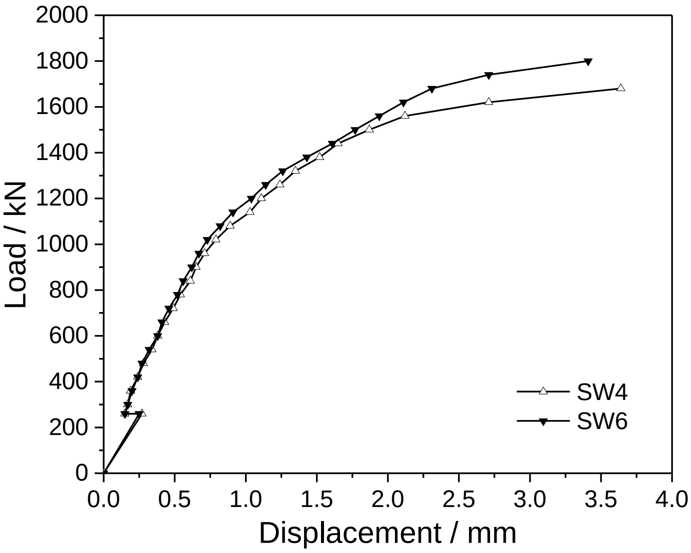


Figure 10. Load-displacement curves of specimens SW4 and SW6

Figure 11 shows the load-displacement curves of specimens SW2, SW4 and SW5. Specimens SW2, SW4 and SW5 were strengthened with steel strips by the same pre-compression stress in the vertical steel strips, but the brick masonry wall was preloaded in different level. From figure 11, it shows when the preload level less than 41% of peak load did not have obvious effect on the peak load, and their load-displacement curves are very similar except for the early ones. When the preload level is less than that can result in cracks in the brick wall, the amount of deformation in the brick wall is relatively small, which does not change the overall behavior of the strengthened specimens.

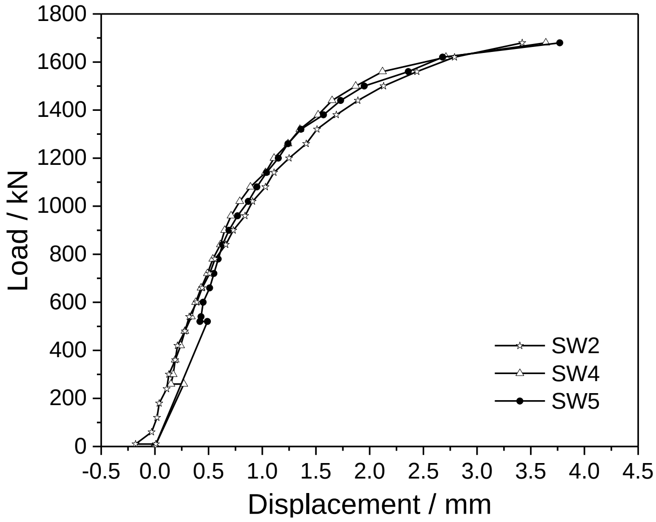


Figure 11. Load-displacement curves of specimens SW2, SW4 and SW5

4. Conclusions

In order to investigate the effect of pre-stress in steel strips to strengthen unreinforced masonry walls under axial loads, seven specimens were fabricated and tested, and the influence parameters included pre-stressing in the steel strips and preload level on the masonry wall. The main conclusions drawn from the results are as follows:

(1) The failure mode of brick masonry walls strengthened by steel strips is characterized by many cracks in the masonry wall, crushing in the weak part of the wall and obvious local buckling in the vertical steel strips.

(2) Using steel strips to strengthen the masonry walls is effective to improve its peak load, continuous cracking load, and the axial stiffness.

(3) Applying pre-compression stress in the vertical steel strips can increase the load of cracking in the single bricks.

(4) Transverse steel strips not only provide lateral support to longitudinal steel strips, but also restrains the masonry wall and further delays the occurrence of continuous cracks. Applying pre-tension stress in the transverse steel strips can make it work in advance, and further improve the peak load and the later axial stiffness of the masonry wall.

Acknowledgments

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